Strain age cracking in nickel-based superalloys

Together with Malmö University, the aerospace supplier GKN Aerospace conducted in-situ diffraction and tomography studies on nickel-based superalloys. As part of a larger project, the synchrotron radiation from PETRA III helped them to gain a better understanding of strain age cracking in the precipitation-hardened nickel superalloys.

CHALLENGE

A major goal for the aerospace industry is to reduce the weight of an aircraft. A lower weight means that the fuel consumption can be reduced and consequently the emission of harmful gases, such as nitrogen oxides (NOx). GKN Aerospace is working on developing next generation jet engine materials: precipitation-hardened nickel-based superalloys. These are heavily alloyed to handle the heat and forces in running jet engines.
More importantly for the aerospace industry, the safety and reliability of the materials used needs to be ensured. In heat-treated components, or parts that have been welded multiple times, so-called strain age cracking (SAC) can occur. Nickel superalloys gain additional strength through the precipitation of γ` phases. During welding or heat treatment the temperature reaches a point at which the γ` phase precipitates and the ductility of the superalloy decreases. If the superalloy is then strained beyond the decreased ductility, cracks can appear and material failure will occur. Nickel superalloys are especially susceptible to this phenomenon due to the rapidity of precipitation and high-volume fraction of γ` precipitates. For example, the SAC can be so severe that some nickel superalloys are labeled as unweldable.
Understanding SAC is impeded by two main factors. On the one hand, SAC occurs at high temperatures that have to be replicated in the experiments. There are few places where in-situ experiments can be conducted at high temperatures, but this is possible at the synchrotron facility PETRA III. On the other hand, SAC involves multiple length scales, from mm down to nm. Covering this range of lengths is challenging for techniques like scanning or transmission electron microscopy (SEM/TEM), but synchrotron radiation is able to do so. Lastly, both temperature and length scales have to be included simultaneously in the experience, making PETRA III a good choice.

Figure 1: Custom load frame used for SAXS, 3DXRD and tomography of nickel superalloys. A Joule heating system is also included. Copied from Vinnova project report number 2019-02584.

METHOD

At the Swedish Materials materials science beamline P21.2 at PETRA III, multiple diffraction and scattering methods were used in combination with in-situ loading and heating of the nickel superalloy samples. The methods included small-angle X-ray scattering (SAXS), 3D X-ray diffraction (3DXRD) and tomography. A load frame was specially developed for these measurements.

ANALYSIS AND SOLUTION

The applied methods covered length scales from mm down to nm. During the heating experiments, misfit strains during precipitation of different phases could be observed. Also, changes in the stiffness of the grains came to light during heating and loading. Nonetheless the experiments did not give a full explanation of SAC. From the measurements, it was possible to deduce that SAC is rooted in different effects at different length scales.

BENEFITS

The brilliant radiation from PETRA III made it possible to inspect precipitation and the mechanical properties of the precipitates at different elevated temperatures and loading conditions. The findings turned out to be an important part of a much larger effort to understand SAC from the nanometer scale up to the millimeter scale. More studies are needed to give a complete view and understanding of SAC in nickel superalloys. PETRA III has once again proved to be a reliable support for industrially relevant research, thanks to its ability to imitate the working and processing conditions of the samples of interest.

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